The Contribution of Cochlear Region and Stimulation Rate to Speech Perception in Cochlear Implant Users

Capstone Document

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Abstract

The objective determination of an optimal stimulation rate for speech perception for cochlear implant users could save time and take the uncertainty out of choosing a rate based on patient preference. Electrically evoked compound action potential (ECAP) temporal response patterns vary across stimulation rates and cochlear regions, and could be useful in predicting an optimal rate. However, it is not clear which area of the cochlea should be used to make that prediction. The goal of this study was to determine which cochlear region contributes the most to speech perception, and whether that contribution is affected by stimulation rate. Twenty-two ears in 20 subjects were tested on Hearing In Noise Test (HINT) sentences, Consonant-Nucleus-Consonant (CNC) phonemes, and Iowa Medial Consonants in three map conditions (basal, middle, or apical electrode sets) using the subject’s daily stimulation rate. Nine subjects were also tested using a rate that produced stochastic ECAP responses, as measured in a previous study. Results revealed significantly better performance using the middle electrodes for sentences and phonemes. For medial consonants, performance using the basal and middle electrodes was equally better than for the apical electrodes. Stimulation rate did not have a significant effect on performance. If ECAPs are to be used to predict an optimal stimulation rate for speech perception, the neural responses of the middle region may be the most appropriate for making that prediction.

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Chapter 1: Introduction and Literature Review

Cochlear implant programming software allows for a number of parameters to be adjusted in an effort to give recipients the maximum amount of benefit from their device. One of these parameters is stimulation rate (i.e., how quickly electric pulses are delivered from the device to the auditory nerve). This parameter is typically chosen based on default parameters or subjective preference. Previous studies have shown that speech perception varies with stimulation rate and that the optimal stimulation rate varies across recipients (Arora, Dawson, Dowell, & Vandali, 2009; Holden, Skinner, Holden, & Demorest, 2002; Loizou, Poroy, & Dorman, 2000; Nie, Barco, & Zeng, 2006; Vandali, Whitford, Plant, & Clark, 2000). Additionally, optimal performance is not always obtained by using the stimulation rate that is preferred by the individual (Arora et al., 2009; Holden et al., 2002; Vandali et al., 2000). An objective method for determining the optimal stimulation rate would save time and could allow for improved speech perception performance without the uncertainty of choosing a rate based only on patient preference.

It is possible that differences in performance as a function of rate are due to underlying temporal response properties of the auditory nerve. This is supported by relationships between speech perception and temporal processing (Busby & Clark, 1999; Cazals, Pelizzone, Saudan, & Boex, 1994; Fu, 2002). Electrically evoked compound action potentials (ECAPs) can be used to measure temporal response properties of the auditory nerve. ECAP responses to pulse trains have been shown to vary with stimulation rate (Hughes, Castioni, Goehring, & Baudhuin, 2012; Rubinstein, Wilson, Finley, & Abbas, 1999; Wilson, Finley, Lawson, & Zerbi, 1997) and may be useful in predicting an optimal stimulation rate. Research, through ECAP testing, has determined that temporal responses of the auditory nerve vary across different regions of the cochlea (Hughes et al., 2012; Wilson et al., 1997). Cochlear implant devices and programming software, however, only allow for one rate of stimulation to be chosen for an entire electrode array. If one rate must be chosen, ECAP measures could be used to predict an optimal stimulation rate. It is not clear, however, which region of the cochlea should be used to make that prediction. The goal of the present study was to determine which region of the cochlea (basal, middle, or apical) contributes the most to speech perception when stimulation is limited to that region and if stimulation rate (daily rate vs. stochastic rate) affects that contribution.

Stochastic Rate

The process by which individuals with normal hearing perceive sound via acoustic hearing differs from the process by which individuals with cochlear implants perceive sound via electric hearing. Two differences relevant to the topic of stimulation rate include spontaneous firing of hair cells and phase-locking. In a healthy cochlea, auditory neurons fire spontaneously in a stochastic nature even when no sound stimulus is present. This spontaneous firing is greatly reduced in the pathologic cochlea, as is typically the case for individuals with cochlear implants (Liberman & Dodds, 1984). In addition, the auditory neural response is altered when neurons are stimulated electrically.

Rather than fibers responding in a relatively independent and stochastic nature as they do in acoustic hearing, they tend to respond much more synchronously. When auditory neurons respond to acoustic stimulation, different populations of neurons phase-lock to different phases of the stimulus. In electric hearing, however, all or most of the stimulated fibers tend to lock to one specific phase of the stimulus (Kiang & Moxon, 1972). If a more natural presentation of sound can improve performance with a cochlear implant, then these differences should be taken into consideration.

Wilson et al. (1997) measured ECAPs in response to increasing stimulation rate in order to describe the response patterns of auditory neurons in electric hearing. At slow rates (up to approximately 200 pulses per second [pps]), nearly all auditory neurons fired with every pulse resulting in ECAPs that were consistent in amplitude with each pulse. As rate was increased, the ECAP response took on an alternating pattern of high and low amplitude. This was the result of neurons entering a refractory period and not recovering in time to discharge with every pulse that was delivered. For example, the response to the first pulse was high in amplitude because many neurons were discharging in reaction to the stimulus. The response to the second pulse was much lower in amplitude because those neurons that discharged in response to the first pulse were in a refractory period. By the time the third pulse occurred, more neurons could respond again because they were out of the refractory period. This continued with each pulse, resulting in an alternating amplitude pattern. As rate was increased even further, the alternation began to decrease and eventually the ECAP response reached a state in which it remained small, but relatively stable in amplitude with each pulse (Wilson et al., 1997).

The marked reduction in alternation and amplitude of the ECAP responses at high rates of stimulation may be due to a desynchronization of auditory neurons. Because the neurons are no longer synchronized, separate small populations of auditory neurons that are roughly equal in size respond to each pulse. This results in the consistently reduced ECAP amplitude pattern (Rubinstein et al., 1999; Wilson et al, 1997). Rubinstein et al. (1999) used a computer model to demonstrate that at high rates of stimulation, simulated auditory neurons took on a "pseudospontaneous" firing pattern which led to less synchronization. Because this is more similar to auditory neuron behavior in acoustic hearing, it may suggest that a better representation of the sound signal would be delivered to the cochlea in electric hearing with higher rates of stimulation (Rubinstein et al., 1999). Additional benefits of pseudospontaneous firing include an expanded dynamic range due to a lower behavioral threshold (Hong, Rubinstein, Wehner, & Horn, 2003) and potentially better temporal processing (Rubinstein et al., 1999).

Wilson et al. (1997) noted that the specific rate at which this apparent desynchronization occurred varied both across electrodes and between subjects, although the extent of variation across electrodes and subjects was not reported. In a cochlear implant, each electrode stimulates a different neural population along the cochlea and each neural population responds differently to that stimulation. This is why variance is seen in ECAP responses across the electrode array (Wilson et al, 1997). Because these responses are not predictable, ECAPs could be measured on an individual basis to determine at exactly which point the desynchronization occurs.

Hughes et al. (2012) defined this point of desynchronization as the *stochastic rate*, or the stimulation rate at which the ECAP response discontinued the alternating amplitude pattern. Hughes et al. (2012) determined the stochastic rate for subjects with cochlear implants by measuring ECAPs at rates of 900, 1200, 1800, 2400, and 3500 pps for one basal, one middle, and one apical electrode. For most subjects, the stochastic rate was higher than the daily stimulation rate used by the subject. In addition, just as reported by Wilson et al. (1997), the stochastic rate varied across individuals and for the three different regions of the cochlea. Stochastic rates fell across the entire range of stimulation rates tested from 900 to 3500 pps with no pattern in regards to site of stimulation. This suggests that if ECAP response patterns are to be used to determine an optimal stimulation rate for a cochlear implant user, the maximum benefit may result from a rate that is varied across electrodes (Hughes et al., 2012).

Stimulation Rate and Speech Perception

The effect of stimulation rate on speech perception has been studied to investigate the hypothesis that higher rates of stimulation will make auditory neurons behave more as they do in acoustic hearing and thus improve speech perception abilities. In addition, higher rates of stimulation should also provide more accurate temporal resolution (Friesen, Shannon, & Cruz, 2005; Fu & Shannon, 2000; Holden et al., 2002; Loizou et al., 2000; Rubinstein et al., 1999; Vandali et al., 2000). Acoustic information coded by the speech processor of the cochlear implant is delivered to the auditory nerve with every pulse. More pulses within a period of time means more opportunities for information delivery within that timeframe and, theoretically, better temporal resolution.

Vandali et al. (2000) tested five subjects using the Nucleus 24 cochlear implant and a processing strategy similar to SPEAK (spectral peak). Stimulation rate was varied between 250, 807, and 1615 pps. Although CNC word and consonant (Peterson & Lehiste, 1962) scores did not change across conditions, CNC vowel scores dropped at 1615 pps. CUNY sentence scores presented at high signal-to-noise ratios (SNRs) remained stable across the conditions, but dropped at 1615 pps when presented at lower SNRs. The researchers noted, however, a large amount of individual variability in performance patterns across the three rates. Several subjects clearly had a preferred stimulation rate in terms of speech perception performance, but that rate differed among subjects. Also of note, when one subject who performed particularly poorly with a rate of 1615 pps was removed from analysis, no significant differences in scores were apparent across rate conditions (Vandali et al., 2000).

Similar results were obtained by Fu and Shannon (2000) using stimulation rates between 50 and 500 pps. Six subjects were included in this study and used the Nucleus 22 cochlear implant with the CIS processing strategy. While vowel and consonant recognition improved as stimulation rate was increased from 50 to 150 pps, an increase in stimulation rate did not lead to an increase in performance beyond 150 pps (Fu & Shannon, 2000). Comparable effects were observed by Friesen et al. (2002) using much higher rates up to the maximum stimulation rates permitted by the cochlear implant processor.

Verschuur (2005) observed speech perception performance across various rates of stimulation for six users of the Med-El Ineraid and COMBI 40+ cochlear implant and the

CIS processing strategy. Subject performance displayed no effects of stimulation rate for BKB sentences in quiet, vowel-consonant-vowel (VCV) tokens, or a synthetic categorical identification measure for rates of 400, 800, and a third rate between 1515 and 2272 (Vershuur, 2005). Weber et al. (2007) found equivalent results for 13 Nucleus Freedom cochlear implant recipients using the ACE processing strategy. These subjects were tested at stimulation rates of 500, 1200, and 3500 on Frieburg monosyllables and Oldenburg sentences and showed no significant different in performance across the stimulation rate conditions (Weber et al., 2007). These studies (Friesen et al., 2002; Fu & Shannon, 2000; Vandali et al., 2000; Verschuur, 2005; Weber et al., 2007) seem to suggest that there is little to no relationship between rate of stimulation and speech perception scores.

In contrast, Loizou et al. (2000) used a Med-El cochlear implant that utilized the CIS processing strategy and stimulation rates of 400, 800, 1400, and 2100 pps. Maximum speech perception performance was obtained for all six subjects at the highest stimulation rate for consonant identification. Subjects tended to reach a plateau in performance between 800 and 2100 pps, with the beginning of the plateau varying among subjects. Vowel identification, on the other hand, did not change as a function of stimulation rate (Loizou et al., 2000).

Likewise, Holden et al. (2002) tested eight subjects using the Nucleus 24 cochlear implant with the ACE processing strategy and found that between the stimulation rates of 720 and 1800 pps, performance on CUNY sentences and CNC phonemes were better for the group at 1800 pps. Two subjects, however, showed better performance using the 720 pps rate, once again highlighting the presence of individual variation (Holden et al., 2002). Similar results were obtained using the same device and strategy in eight subjects by Arora et al. (2009) using stimulation rates of 275, 350, 500, and 900 pps. Although CNC word scores exhibited no effect of stimulation rate, SIT sentences in quiet and noise were better at 500 and 900 pps than at 272 pps (Arora et al, 2009).

Nie et al. (2006) obtained mixed results on five users of the Med-El COMBI 40+ with stimulation rates of 1000, 2000, and 4000 pps. Recognition scores of medial vowels showed no effect of stimulation rate while medial consonants and HINT sentences (Nilsson, Soli, & Sullivan, 1994) in quiet improved with increasing rate. HINT sentence scores in noise, however, were best at 2000 pps (Nie et al., 2006).

The effect of stimulation rate on speech perception performance is clearly not well-defined at this point. There are no clear trends related to cochlear implant manufacturer, device, or processing strategy. All of the aforementioned studies used post-lingually deafened adults as subjects, other than Nie et al. (2006) where a combination of pre- and post-lingually adults participated. The discrepancies in results between studies (Arora et al., 2009; Friesen et al., 2002; Fu & Shannon, 2000; Holden et al., 2002; Loizou et al., 2000; Nie et al., 2006; Vandali et al., 2000; Verschuur, 2005; Weber et al., 2007) may be due to a variety of other experimental design parameters including amount of practice with a given stimulation rate, number of electrodes utilized, stimulation mode, stimulus presentation level, or previous experience with the cochlear implant. In addition, it is evident that individual differences among cochlear implant users may play a role in the variability of results.

Some subjects seemed to have a distinct advantage when using a certain stimulation rate, which may or may not be related to that subject's stochastic rate. It is also a possibility that some of the studies previously described did not use high enough stimulation rates to cause desynchronization of the auditory neurons, or that the rates used were not close enough to the individual's stochastic rate. This may have played a role in why improvement in speech perception with increasing stimulation rate was not seen.

Modulation Detection Thresholds

Stimulation rate has been shown to affect the temporal responses of the auditory nerve (Hughes et al., 2012; Rubinstein et al., 1999; Wilson et al., 1997). These responses relate to temporal processing, which has been shown to be related to speech perception (Cazals et al., 1994; Fu, 2002). This relationship may explain why speech perception varies with stimulation rate. Modulation detection thresholds (MDTs) are temporal measures that describe the minimum amount of modulation required for an individual to detect that amplitude modulation is occurring. Lower MDTs and amplitude modulation transfer functions resembling those of normal hearing individuals have been associated with better speech perception in individuals with cochlear implants (Cazals et al., 1994; Fu, 2002). By measuring how MDTs change with stimulation rate, information may be gained regarding how speech perception changes with stimulation rate.

Pfingst, Xu, and Thompson (2007) studied the effects of rate of stimulation on MDTs in 12 users of the Nucleus 24 cochlear implant. Modulated signals were presented to one basal, one middle, and one apical electrode using stimulation rates of 250 and

4000 pps. Overall, subjects displayed better MDTs for the 250 pps rate (Pfingst et al., 2007). This finding is supported by Galvin and Fu (2005), who determined that six individuals with either the Nucleus 22 or Nucleus 24 cochlear implant exhibited better MDTs when a stimulation rate of 250 pps was used than when a rate of 2000 pps was used. They speculated that this may mean individuals with cochlear implants do not have access to the temporal cues provided by a higher stimulation rate, and therefore do not show improved temporal resolution (Galvin & Fu, 2005).

Arora, Vandali, Dowell, and Dawson (2011) used stimulation rates of 275, 350, 500, and 900 pps to determine at which rate the best acoustic and electric MDTs occurred for ten users of the Nucleus 24 cochlear implant. The best electric MDTs at 20 dB below most comfortable level (MCL) were obtained using stimulation rates at 500 pps and below. The worst MDTs at that same level were obtained using a 900 pps rate. No effect of stimulation rate was seen at MCL for electric MDTs. The opposite was true of acoustic MDTs at MCL where the best performance occurred at 500 pps and above. Here, no effect of stimulation rate was seen 20 dB below MCL (Arora et al.).

Gap detection is another measure of temporal processing. Busby and Clark (1999) measured gap detection thresholds at stimulation rates of 200, 500, and 1000 pps in 15 subjects implanted with a Nucleus device. Overall, no effect of stimulation rate was observed in terms of gap detection thresholds (Busby & Clark, 1999).

These studies (Arora et al, 2011; Busby & Clark, 1999; Galvin & Fu, 2005; Pfingst et al., 2007) present mixed results on how stimulation rate affects temporal processing in individuals with cochlear implants. For the most part, however, there does not seem to be strong evidence to support that an increase in stimulation rate equates to better temporal processing. If an individual's stochastic rate is the optimal stimulation rate, we might expect to see better MDTs and gap detection thresholds at higher rates of stimulation. It is also possible that benefits in speech perception would not result unless the stimulation rate was very close to the stochastic rate, which may not have been the case in all or some of these studies (Arora et al, 2011; Busby & Clark, 1999; Galvin & Fu, 2005; Pfingst et al., 2007).

Determining Stimulation Rate

As previously mentioned, stimulation rate is currently a cochlear implant parameter that is typically chosen based on subjective preferences of the user. In essence, whichever stimulation rate sounds the best to the cochlear implant recipient is the one that is chosen. In many cases, however, the preferred stimulation rate is not the same as the optimal stimulation rate as defined by speech perception scores. A small number of the previously discussed studies (Arora et al., 2009; Holden et al., 2002; Vandali et al., 2000) not only measured speech perception as it varies by rate, but also asked subjects, all of whom were post-lingually deafened adults, about their preferences.

The subjects in the Vandali et al. (2000) study preferred stimulation rates of 250 and 807 pps over 1615 pps for conversation in quiet and noise. Two hundred and fifty pps was preferred for listening to environmental sounds. For listening to music, however, a stimulation rate of 1615 pps was preferred. No preference was reported for listening to the television. In contrast, Holden et al. (2002) reported that the majority of subjects preferred a stimulation rate of 1800 pps over 720 pps. For both of these studies (Holden et al., 2002; Vandali et al., 2000) the preferred rate of stimulation generally matched with the rate at which optimal speech perception performance was obtained, but not for all subjects or in all listening situations.

Arora et al. (2009) found that the majority of subjects preferred 500 pps in quiet, noise, and overall. The other rates tested in this study (Arora et al., 2009) were 275, 350, and 900 pps. Preferences did not show a clear relationship with speech perception scores. Many subjects preferred using rates that differed from the stimulation rate in which they demonstrated the best speech perception. Arora et al. (2009) also noted that five of eight subjects in this study decided at the end of the study to use a rate other than the daily rate they had been using prior to the study. These studies (Arora et al., 2009; Holden et al., 2002; Vandali et al., 2000) do not show a straightforward trend regarding the relationship between optimal stimulation rate and preference, but they do attest to the imprecise nature of the current method of stimulation rate selection.

Several studies (Kiefer, Hohl, Stürzebecher, Pfennigdorff, & Gstöettner, 2001; Shpak, Berlin, & Luntz, 2004) have attempted to find a more objective procedure of selecting a stimulation rate. Shpak et al. (2004) compared the ECAP responses of five Nucleus 24 recipients utilizing the ACE processing strategy to each subject's preferred stimulation rate. ECAPs varied depending on which electrode was used, but electrodes 7, 11, and 15 were found to be predictive of preferred stimulation rate. Subjects who preferred lower stimulation rates (900 and 1200 pps) demonstrated longer ECAP recovery times than those subjects preferring a higher stimulation rate of 1800 pps. This suggests that people with longer refractory periods who are implanted with cochlear implants may prefer a slower stimulation rate, those with shorter refractory periods may prefer a faster stimulation rate, and that ECAPs may be a potential predictor of preferred stimulation rate. It is important to note, however, that only preferred stimulation rate was taken into consideration and not optimal stimulation rate. Likewise, Kiefer et al. (2001) compared various user preferences, including stimulation rate, and speech perception scores to ECAP results in 11 Nucleus 24 recipients. No relationship could be found, however, because preferences and performance were relatively uniform across participants regardless of ECAP results (Kiefer et al. 2001). It is not clear whether ECAPs are a good predictor of optimal stimulation rate, as previous studies (Kiefer et al. 2001; Shpak et al., 2004) have presented mixed results. It is clear however, that if ECAPs are to be used, a feasible method is not currently available.

Cochlear Region

If ECAPs can be used to predict an optimal stimulation rate, one region of the cochlea would have to be chosen to represent the entire cochlea, as ECAPs vary across the cochlea (Hughes et al., 2012; Wilson et al., 1997). The region that provides for the best speech perception may be the best choice. Several studies (Fu & Shannon, 1999; Hochmair et al., 2003; Pfingst, Franck, Xu, Bauer, & Zwolan, 2001) have investigated speech perception abilities of cochlear implant recipients using only specific portions of the electrode array and have demonstrated varied results.

Fu and Shannon (1999) stimulated sets of four widely-spaced electrodes in three users of the Nucleus 22 cochlear implant. Maps were shifted basally to apically along the cochlea. Fu and Shannon (1999) found that vowel and consonant recognition scores improved as the stimulated electrodes moved to a more apical location.

In contrast, Hochmair et al. (2003) stimulated a set of four adjacent electrodes in ten users of the Med-El COMBI 40+ cochlear implant in either the basal, middle, or apical cochlear regions. Results revealed that the apical condition produced the worst scores on a two-digit numbers speech perception task and that the middle electrode map condition yielded the best scores (Hochmair et al., 2003). Similarly, Pfingst et al. (2001) stimulated basal, middle, and apical regions of the cochlea using 11 of 22 electrodes per map. Ten subjects implanted with either the Nucleus 22 or 24 cochlear implant were tested using CNC words and CUNY sentences. The highest scores were obtained using the middle region of the electrode array, but no significant difference was found between basal and apical scores (Pfingst et al., 2000). The differences in results of these studies may be due to differences in the spacing and number of the stimulated electrodes across the three studies. For example, the maps used by Fu and Shannon (1999) and Pfingst et al. (2001) covered a greater portion of the cochlea than the maps used by Hochmair et al. (2003).

Related studies (Geier & Norton, 1992; Shannon, Galvin, & Baskent, 2001) have taken an alternative approach to isolating areas of the cochlea and removed either basal, middle, or apical sections of the electrode array. Geier and Norton (1992) removed five electrodes in each region for six subjects, while Shannon et al. (2001) varied the number of electrodes removed from two to eight for five subjects. In both of these studies (Geier & Norton, 1992; Shannon et al., 2001), speech perception testing suffered the most with the removal of the apical electrodes. Geier and Norton (1992) reported the best performance when the middle electrode region was removed while Shannon et al. (2001) reported the best performance when the basal electrode region was removed. Subjects in both studies used the Nucleus 22 cochlear implant and mentioned a notable amount of subject variability in performance.

The results of the studies (Geier & Norton, 1992; Shannon et al., 2001) in which sections of the electrode array were removed are consistent with the results obtained by Fu and Shannon (1999) and seem to implicate the apical region as the most important for speech perception. The Hochmair et al. (2003) study, however, seems to imply the opposite. Generally speaking, there does not appear to be conclusive evidence regarding which area of the cochlea is most important for the perception of speech in users of cochlear implants.

Along with studying the effect of stimulation rate on MDTs, as previously discussed, Pfingst et al. (2007) also observed that site of stimulation did not have a consistent effect on MDTs. The best MDTs using a rate of 250 pps were obtained from the apical electrode and the best MDTs using a rate of 4000 pps were obtained from the basal electrode. The best overall MDTs were obtained using 250 pps on the apical electrode and the worst MDTs were obtained using the 4000 pps rate on the apical electrode. Differences between apical and middle MDTs were significantly different, however differences between basal and middle MDTs were not. These data suggest that the apical region combined with lower stimulation rates may be crucial for speech perception, and also that different regions of the cochlea respond differently to varying stimulation rates (Pfingst et al. 2007). This may be related to differences in the ECAP responses across the cochlea that have been reported by other studies (Hughes et al., 2012; Wilson et al., 1997).

The Present Study

There does not appear to be conclusive evidence regarding which area of the cochlea, if any, dominates speech perception. The purpose of the present study was to determine if a particular region of the cochlea contributes more to speech perception when stimulation is limited to the basal, middle, or apical electrodes. Temporal responses have been shown to vary across the cochlea and across individuals (Hughes et al., 2012; Wilson et al., 1997). Therefore, if temporal response properties at the level of the auditory nerve contribute to speech perception, then the cochlear region that contributes the most to speech perception would be different across individuals, as well. The present study also attempted to determine if the contribution of a specific cochlear region varies when using a subject’s daily stimulation rate versus that subject’s stochastic rate. Higher rates of stimulation produce more stochastic responses from the auditory nerve (Rubinstein et al., 1999). If these responses contribute to speech perception, then a subject’s stochastic rate would allow for better speech perception than their daily rate.

Chapter 2: Methods

Subjects

Twenty-two ears were tested in 20 individuals with cochlear implants (three Nucleus CI512 [Cochlear Ltd., Lane Cove, New South Wales, Australia], six Nucleus 24RE(CA) [Cochlear Ltd., Lane Cove, New South Wales, Australia], six Nucleus 24R(CS) [Cochlear Ltd., Lane Cove, New South Wales, Australia], three HiResolution 90K [Advanced Bionics, Sylmar, California, USA], and four Clarion CII [Advanced Bionics, Sylmar, California, USA]). All subjects were tested using their daily stimulation rate in three map conditions using a subset of only basal, middle, or apical electrodes. Inclusion criteria were HINT sentence scores above 50% correct in quiet when tested in the cochlear implant only condition. This was due to the difficult nature of the present study's speech perception tasks attributed to the use of a limited electrode array.

Nine of these subjects were also tested using their stochastic rate in the three map conditions, for a total of six maps. The purpose of this subgroup was to investigate the effects of stimulation rate on speech perception performance for each of the cochlear regions. These subjects participated in a previous study (Hughes et al., 2012) in which stochastic rates were determined for one basal, one middle, and one apical electrode. Subjects were required to have measureable ECAPs on all three electrodes in order to determine stochastic rate for each cochlear region. These subjects also needed to have a device that supported speech processing with their stochastic rate. Namely, the Nucleus 24R(CS) cannot stimulate at 3500 pps.

Demographic information including age and duration of deafness for all subjects can be found in Table 1. All subjects were compensated for their participation. This study was approved by the Boys Town National Research Hospital Institutional Review Board.

Stochastic Rates

Stochastic rates used in the present study were determined in a previous study (Hughes et al., 2012). Briefly, Hughes et al. (2012) determined stochastic rates by measuring the amplitude of ECAPs on one basal, one middle, and one apical electrode. The Cochlear Corporation electrode array has 22 electrodes where electrode 1 is the most basal and electrode 22 is the most apical. For subjects using a Nucleus device, typically the basal, middle, and apical electrodes from which ECAPs were measured were electrodes 3, 11, and 20, respectively. The Advanced Bionics electrode array has 16 electrodes where electrode 16 is the most basal and electrode 1 is the most apical. For these subjects, the basal, middle, and apical electrodes were electrodes 14, 8, and 1, respectively. ECAPs were measured for each of these electrodes using pulse trains at stimulation rates of 900, 1200, 1800, 2400, and 3500 pps. A subtraction method as described by Hay-McCutcheon et al. (2005) was used to derive the response of the auditory nerve to individual pulses within the train. Amplitudes were calculated, normalized to the first pulse in a train of 21 pulses, and graphed over time. Alternation depth was calculated as the average amplitude of the odd numbered pulses (except the first pulse) minus the average amplitude of the even numbered pulses. Stochastic rate was

Table 1. Subject demographic information. Bolded subjects participated using both their daily and stochastic stimulation rates.

Subject	Device	Ear	Duration Deafness (yrs, mos)	Age at CI (yrs, mos)	Duration CI Use (yrs, mos)	Etiology
R2*	Nucleus 24R(CS)	R	3,5	51,8	9,3	Noise Induced, Hereditary
R6	Nucleus 24R(CS)	R	6,0	44,5	17,8	Autoimmune Disease
R7	Nucleus 24R(CS)	R	5,10	62,2	6,8	Unknown, Progressive
R10	Nucleus 24R(CS)	R	2,0	61,10	8,6	Unknown, Progressive
R15	Nucleus 24R(CS)	R	0,10	1,4	10,9	Meningitis
R16†	Nucleus 24R(CS)	R	18,1	18,1	6,11	Unknown
F1	Nucleus 24RE(CA)	L	54,3	60,7	4,2	Unknown
F4	Nucleus 24RE(CA)	L	17,6	17,6	4,0	Ototoxicity
F7	Nucleus 24RE(CA)	R	28,1	39,1	4,5	Unknown
F10	Nucleus 24RE(CA)	R	8,3	8,3	5,7	Waardenburg Syndrome
F13	Nucleus 24RE(CA)	L	4,4	35,2	3,3	Unknown, Progressive
F15†	Nucleus 24RE(CA)	L	22,10	22,10	2,2	Unknown
N1*	Nucleus CI512	L	9,0	58,3	2,7	Noise Induced, Hereditary
N4	Nucleus CI512	R	0,6	13,4	1,5	Unknown
N5	Nucleus CI512	R	1,8	50, 9	0,9	Sudden SNHL
C8	Clarion CII	L	0,4	55,7	11,1	Sudden SNHL
C13	Clarion CII	L	20,0	77,2	8,8	Genetic- Unspecified
C14	Clarion CII	R	0,2	6,2	10,0	Mondini Malformation
C24	Clarion CII	R	15,9	67,4	9,9	Unknown, Progressive
C29	HiRes 90K HF 1J	R	21,9	30,11	3,10	Meningitis
C37	HiRes 90K HF 1J	L	1,7	1,7	11,1	Unknown
C39	HiRes 90K HF 1J	L	0,6	63,0	2,7	Unknown

*†Two devices from bilaterally implanted subjects.

defined as the lowest rate at which there was no significant difference between even and odd pulse amplitudes (Hughes et al., 2012).

Procedure

All subjects using a Nucleus device were tested using a laboratory Nucleus Freedom processor with a programming pod interface. A laboratory processor was used so that all subjects were tested using a processor that was known to be functioning correctly and to control for variability that may have resulted from personally owned processors. Impedances were checked at the beginning of each testing period. Maps were created using Cochlear Corporation's Custom Sound 3.2 programming software (Cochlear Ltd., Lane Cove, New South Wales, Australia) to stimulate three separate areas of the cochlea: basal, middle, and apical. Basal maps included only electrodes 2 through 8, middle maps included only electrodes 9 through 15, and apical maps included only electrodes 16 through 22. Exceptions were made for one subject (F10) due to abnormal impedances on electrodes 17 and 20. For this subject, the apical map included electrodes 14 through 16, 18, 19, 21, and 22. For all subjects, each map utilized seven electrodes. Map details for all subjects can be found in Table 2.

All Nucleus maps that were created used a frequency range of 188-7938 Hz and seven maxima (because only seven electrodes were available in each map). The processing strategy was chosen to be the same as that regularly used by the subject (see Table 2) so that the subject did not have to adapt to a new processing strategy. Threshold (T) and comfort (C) levels were determined behaviorally for three electrodes in each map. For the basal map, T and C levels were found for electrodes 2, 5, and 8. For the

Table 2. Daily and stochastic map details. Bolded subjects participated using both their daily and stochastic stimulation rates. Stochastic rates are indicated for all subjects, though not all subjects participated using these rates due to device and/or time limitations. NR denotes no measureable ECAP response obtained. DNT refers to subjects for whom ECAPs were not measured.

Subject	Strategy	Electrode Set (Basal; Middle; Apical)	Maxima	Daily Rate (pps)	Daily Map Pulse Width (µS)	Stochastic Rate (pps) (Basal; Middle; Apical)	Stochastic Map Pulse Width (µS) (Basal; Middle; Apical)
R2	ACE	2-8; 9-15; 16-22	7	500	25	3500, 3500, 3500	
R6	ACE	2-8; 9-15; 16-22	7	1200	25	2400, 2400, 3500	
R7	ACE	2-8; 9-15; 16-22	7	900	25	2400, 3500, 2400	
R10	ACE	2-8; 9-15; 16-22	6	1200	25	2400; 1800; 2400	25, 25, 25
R15	ACE	2-8; 9-15; 16-22	7	900	25	DNT	
R16	ACE	2-8; 9-15; 16-22	7	1200	25	DNT	
F1	ACE	2-8; 9-15; 16-22	7	900	25	1800; 1800; 2400	25; 25; 12
F4	ACE	2-8; 9-15; 16-22	7	900	25	3500, 3500, 3500	
F7	ACE	2-8; 9-15; 16-22	7	900	25	3500*; 2400; 3500	9.6*; 12; 9.6
F10	ACE	2-8; 9-15; 14-16, 18, 19, 21,22	7	900	25	1800; 1800; 1800	25; 25; 25
F13	ACE	2-8; 9-15; 16-22	7	1800	25	DNT	
F15	ACE	2-8; 9-15; 16-22	7	1800	25	DNT	
N1	ACE	2-8; 9-15; 16-22	7	500	25	2400; 2400; 3500	12; 12; 9.6
N4	ACE	2-8; 9-15; 16-22	7	720	25	3500*; 2400; 3500	9.6*; 12; 9.6
N5	ACE	2-8; 9-15; 16-22	7	900	25	3500; 3500; 2400	9.6; 9.6; 12
C8	HiRes-P 120	15-11; 10-6; 5-1	N/A	3712	18	NR	
C13	HiRes-P 120	15-11; 10-6; 5-1	N/A	3093	21.6	DNT	
C14	HiRes-S	15-11; 10-6; 5-1	N/A	829	121.2	NR	
C24	HiRes-S 120	15-11; 10-6; 5-1	N/A	3712	18	2400, 3500, NR	
C29	HiRes-S 120	15-11; 10-6; 5-1	N/A	3712	18	2400, 3500, 3500	27.8; 18.9; 18.9
C37	HiRes-P 120	15-11; 10-6; 5-1	N/A	3712	18	NR	
C39	HiRes-S 120	15-11; 10-6; 5-1	N/A	3712	18	3500; 3500; 2400	18.9; 18.9; 27.8

*These maps were not tested due to voltage compliance limits.

middle map, T and C levels were found for electrodes 9, 12, and 15. For the apical map, T and C levels were found for electrodes 16, 19, and 22. All other T and C levels were interpolated by the software. T level was set at the minimum level where the subject could count two, three, or four 500 ms pulses 100% of the time. C level was set at *loud but comfortable* per Cochlear Corporation's recommended protocol. Subjects were given a loudness scale ranging from 1 (*just noticeable*) to 10 (*too loud*) to help them determine when stimulation was *loud but comfortable* (7 on the scale). C levels were swept and balanced according to patient report for each of the three maps. Before testing began, the subject was asked to estimate the overall loudness of the settings and global adjustments were made until a level of 6, or *most comfortable*, was obtained. Gains and/or volume were increased if necessary to achieve an overall comfortable level of loudness.

Three maps were created in a similar fashion for subjects using an Advanced Bionics device. Differences in procedure are noted here. These subjects were tested using a laboratory Harmony processor and computer programming interface (CPI). Maps were created using Advanced Bionics' Soundwave 2.0 programming software (Advanced Bionics, Sylmar, California, USA). Basal maps included only electrodes 11 through 15, middle maps included only electrodes 6 through 10, and apical maps included only electrodes 1 through 5. Each map utilized five electrodes. Based on Advanced Bionics' recommended protocol, T level was set to where the patient could just notice the sound and most comfortable (M) level was set to where the subject indicated sounds were *most comfortable,* which is a rating of 6 on the loudness scale. T and M levels were measured for every other electrode in each map (three electrodes per map) and interpolated for the remaining electrodes.

A Ling sound check (/ɑ/, /u/, /i/, /s/, /ʃ/, /m/) was performed with each map to ensure the subject could detect a range of speech frequencies. All subjects were able to detect the Ling sounds in all map conditions. Before beginning the speech-perception testing, one list from the Common Phrases test (Robbins, Renshaw, & Osberger, 1991) was practiced with the subject using live voice stimuli. The subject was asked to repeat each of ten sentences three times: 1) without visual cues, 2) with visual cues if needed, 3) again without visual cues. The purpose of this exercise was to briefly familiarize the subject with the new map.

Speech perception materials were presented in the sound field at 60 dB SPL in a sound-treated booth. The audiometer was calibrated for each speech-perception task prior to each subject's testing period. Bilaterally implanted subjects or those utilizing a hearing aid were tested using only the cochlear implant included in the study. The choice of which ear to include in the present study was based on ECAP results obtained by Hughes et al. (2012) and/or speech perception inclusion criteria. Three speech-perception tests were administered to every subject in each map condition. This included two HINT sentence lists, one 50-item CNC word list, and one 70-item Iowa Medial Consonant Test randomization (Tyler, Preece, & Lowder, 1983). The Iowa Medial Consonants included /b/, /d/, /f/, /g/, /dʒ/, /k/, /m/, /n/, /p/, /s/, /ʃ/, /t/, /v/, and /z/ in an /ɑ/-consonant-/ɑ/ (ɑCɑ) context. The CNC word lists were taken from the original ten lists and were chosen from those found to be similar in mean score (Skinner et al., 2006). This test allowed for both word and phoneme scores to be calculated, however only phoneme scores were reported due to floor effects for word scores. Responses for the HINT sentences and CNC words were given orally. For the Iowa Medial Consonant Test, subjects were asked to indicate the sound they heard from a closed set of 14 consonants by selecting their response via computer touch screen. Test order, specific lists, and map conditions (basal, middle, apical) were all randomized across subjects.

For the nine subjects who also participated in this study using maps based on their stochastic rates, testing was completed in two sessions to minimize listener fatigue. The first session consisted of creating the maps and the second session consisted of the speech perception testing. Two maps for each participant were created per cochlear region for a total of six maps for each subject. One map using each electrode set used the subject's daily stimulation rate and the other used the subject's stochastic rate as determined previously by Hughes et al. (2012). Because using only a subset of electrodes was a significant change from each subject's regularly used map, the daily and stochastic maps were considered to be equally novel despite the familiarity of each subject with their daily stimulation rate. Two subjects (N4 and N7) were only tested using five maps. Subject N4 did not experience any perception of sound on any electrode in the basal stochastic map, which used a stimulation rate of 3500 pps. For subject N7, the basal stochastic map was not judged to be loud enough without exceeding voltage compliance limits. This map also used a stimulation rate of 3500 pps. Additionally, one exception was made to the number of maxima for subject R10. This subject used six maxima for each map because the Nucleus 24R implant does not allow for seven maxima when a rate of 2400 pps is used. For subjects using an Advanced Bionics device, the exact stochastic stimulation rate could not always be obtained due to limitations of the software. In such cases, the closest available stimulation rate was used instead. The actual rate never differed from the desired rate by more than 35 pps. Map creation and speech perception testing used the same procedure as previously described.

Chapter 3: Results

The primary purpose of this study was to determine whether a particular region of the cochlea (basal, middle, or apical) contributes more to speech perception by limiting stimulation to a specific set of electrodes. Figure 1 displays the mean speech-perception scores by electrode set for sentences (left panel), phonemes (center panel), and medial consonants (right panel). Error bars indicate one standard deviation above the mean. For all stimuli, mean performance was highest for the middle electrodes. A one-way repeated-measures analysis of variance (ANOVA) revealed a significant main effect (α = .05) of electrode set for sentences ($F_2 = 16.43$), phonemes ($F_2 = 16.71$), and medial consonants ($F_2 = 11.09$). Post-hoc analyses (Tukey's test, $\alpha = 0.05$) revealed a significant difference between mean scores for the basal and middle electrodes and between the middle and apical electrodes for both sentences and phonemes. The difference in mean scores between the basal and apical electrodes was not significant for sentences or phonemes. For medial consonants, the difference in mean scores was significant between the middle and apical electrodes and between the basal and apical electrodes. The difference in mean scores between the middle and basal electrodes was not significant for medial consonants.

Table 3 displays subject counts indicating the number of subjects whose best performance occurred for a given electrode set for each measure. Equal performance in

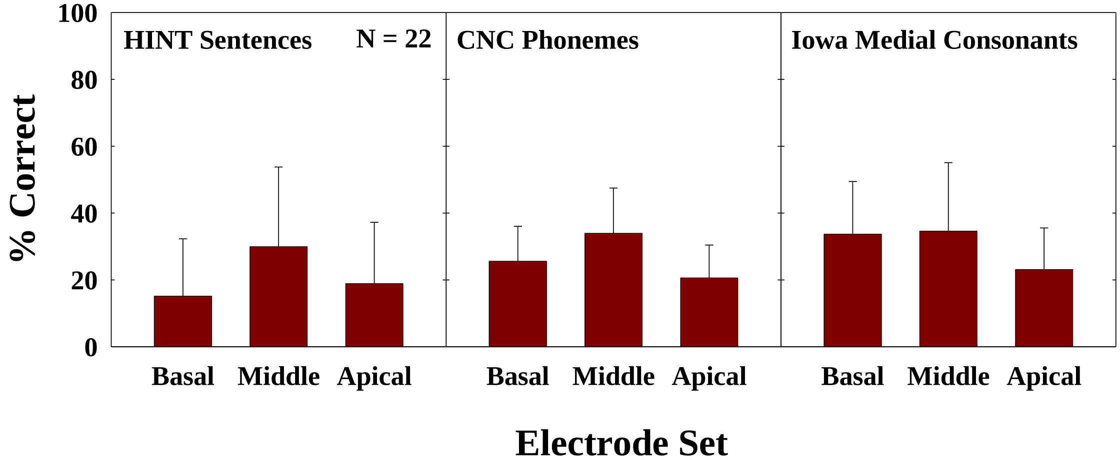

Figure 1. Mean speech perception performance by electrode set for HINT sentences (left), CNC phonemes (middle), and Iowa Medial Consonants (right). Error bars indicate one standard deviation above the mean.

Table 3. Subject distribution by stimulus and electrode set. Counts indicate the number of subjects whose best performance occurred for a given electrode set for each test measure. Equal performance with two electrode sets for a stimulus was counted for both electrode sets. All subjects are included (N= 22).

	HINT Sentences	CNC Phonemes	Iowa Medial Consonants
Basal	1	5	13
Middle	15	15	9
Apical	6	2	2

two electrode sets for a stimulus was counted for both electrode sets. As shown in Table 3, the electrode set of best performance varied across individuals. For sentences and phonemes, the majority of subjects performed best using the middle electrodes. For medial consonants, however, the majority of subjects performed best using the basal electrodes.

Figure 2 displays mean performance for the subset of seven subjects tested using daily and stochastic rate for all six maps. Only seven subjects are included in this figure because two subjects were excluded for whom voltage compliance limits precluded testing with the basal map using the stochastic rate. Results are displayed for daily (red bars) and stochastic (yellow bars) rates by electrode set for sentences (left panel), phonemes (center panel), and medial consonants (right panel). Error bars indicate one standard deviation above the mean. Again, mean performance was highest for the middle electrodes in all stimulus conditions. A two-way repeated-measures ANOVA ($\alpha = 0.05$) was used to assess the factors of rate (daily vs. stochastic) and electrode set (basal, middle, apical). Results revealed a significant effect of electrode set for sentences ($F_2 = 6.77$), phonemes ($F_2 = 6.64$), and medial consonants ($F_2 = 5.17$). There was no significant effect of rate for sentences ($F_1 = 2.42$), phonemes ($F_1 = 1.36$), or medial consonants ($F_1 = 1.10$). There was a significant interaction between rate and electrode set for medial consonants ($F_2 = 5.43$) where the stochastic rate yielded higher scores than the daily rate for only the apical electrodes. There was no significant interaction between rate and electrode set for sentences ($F_2 = 2.13$) or phonemes ($F_2 = 3.22$). Post-hoc analyses (Holm-Sidak test, $\alpha = 0.05$) revealed a significant difference between mean scores for sentences

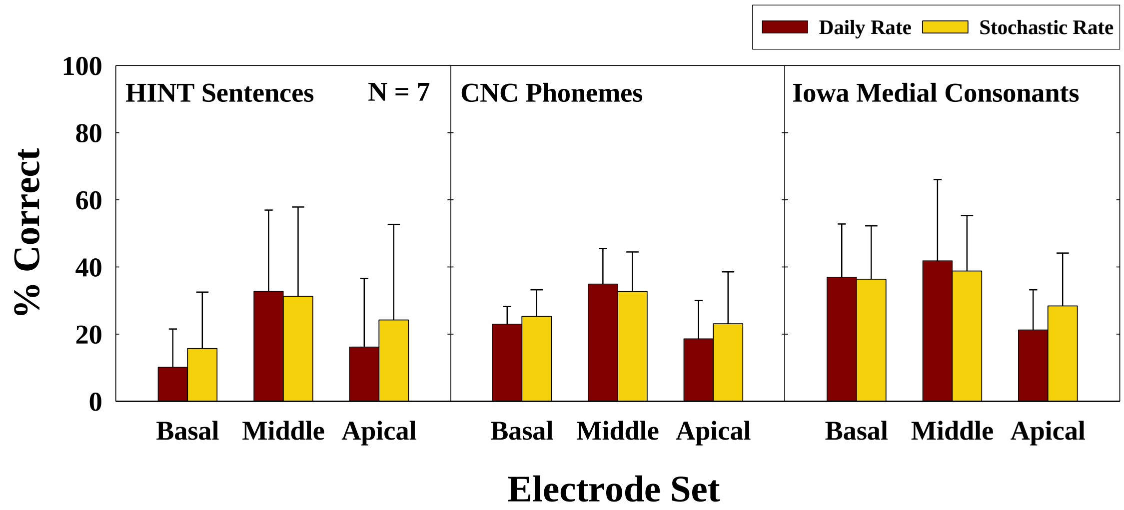

Figure 2. Mean speech perception performance using daily (red bars) and stochastic (yellow bars) stimulation rates by electrode set for HINT Sentences (left), CNC Phonemes (middle), and Iowa Medial Consonants (right). Error bars indicate one standard deviation above the mean.

and for phonemes between the basal and middle electrodes and between the middle and apical electrodes. The differences in mean scores for the basal and apical electrode sets were not significant for sentences or phonemes. For medial consonants, there was a significant difference in mean scores between the middle and apical electrodes and the basal and apical electrodes. No significant difference in mean scores was found between the basal and middle electrodes.

Table 4 displays subject counts for the subset of subjects tested in all six map conditions (daily and stochastic rates). Counts indicate the number of subjects whose best performance occurred with a given electrode set for each test measure and stimulation rate. Numbers in parentheses represent subject counts for best overall performance across daily and stochastic rate within each test measure. The middle electrodes allowed for the best speech perception scores in the majority of subjects for sentences and phonemes, consistent with mean scores displayed in Figure 2. For medial consonants, subject counts for best performance are split relatively evenly between the basal and middle electrodes. Subject counts are also split somewhat evenly between daily and stochastic stimulation rate- nearly equal numbers of subjects performed best when using their daily stimulation rate as compared to those who performed best using their stochastic stimulation rate. This is consistent with the previously discussed results which revealed no significant difference between mean performance using daily and stochastic rate.

Figure 3 shows individual performance for each electrode set (indicated by different symbols) as a function of daily and stochastic rate for sentences (left panel), phonemes (middle panel), and medial consonants (right panel). The diagonal dashed line

Table 4. Subject distribution by stimulus, rate, and electrode set for the subgroup of subjects tested in all six map conditions (N = 7). Counts indicate the number of subjects whose best performance occurred with a given electrode set for each test measure and stimulation rate. Parentheses denote subject counts for best overall performance across daily and stochastic rates within each test measure.

	HINT Sentences		CNC Phonemes		Iowa Medial Consonants	
	Daily	*Stochastic*	*Daily*	*Stochastic*	*Daily*	*Stochastic*
Basal	0 (0)	0 (0)	0 (0)	3 (1)	4 (1)	2 (2)
Middle	6 (4)	5 (1)	7 (3)	3 (3)	3 (2)	3 (1)
Apical	1 (0)	2 (2)	0 (0)	1 (0)	0 (0)	2 (1)

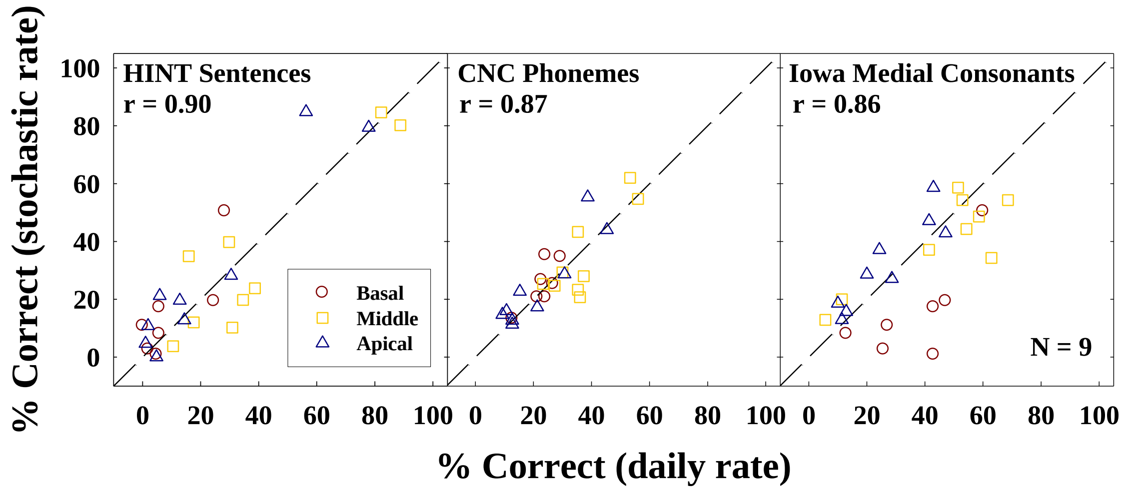

Figure 3. Individual performance for each electrode set (indicated by different symbols) as a function of daily and stochastic rate for HINT Sentences (left), CNC Phonemes (middle), and Iowa Medial Consonants (right). The diagonal dashed line represents equal performance using daily and stochastic rate. Correlation coefficients are given for each plot.

represents equal performance using the two rates. There was a significant positive correlation (Pearson, $\alpha = 0.05$) between performance using daily and stochastic stimulation rates for sentences ($r = 0.90$), phonemes ($r = 0.87$), and medial consonants ($r = 0.86$). This further supports that there were no significant differences in performance using daily and stochastic rates.

Figure 4 displays individual patterns of performance (dashed lines and symbols, left axis) and stochastic rate (solid lines, right axis) across electrodes for the nine subjects tested using both their daily and stochastic rates. Only performance using stochastic rate is shown because it was of interest to examine whether performance and stochastic rate varied in the same way across the cochlea. For a few subjects, the patterns of speech perception performance across electrodes follow the same pattern as stochastic rate across electrodes. That is, an increase in stochastic rate was accompanied by an increase in performance. Subject C39 is an example of this for all stimulus measures. For others there seemed to be an inverse relationship where increases in stochastic rate were associated with decreases in performance, such as for subject R10. Many subjects, however, did not seem to demonstrate any clear relationship between patterns in performance and stochastic rate across electrode sets.

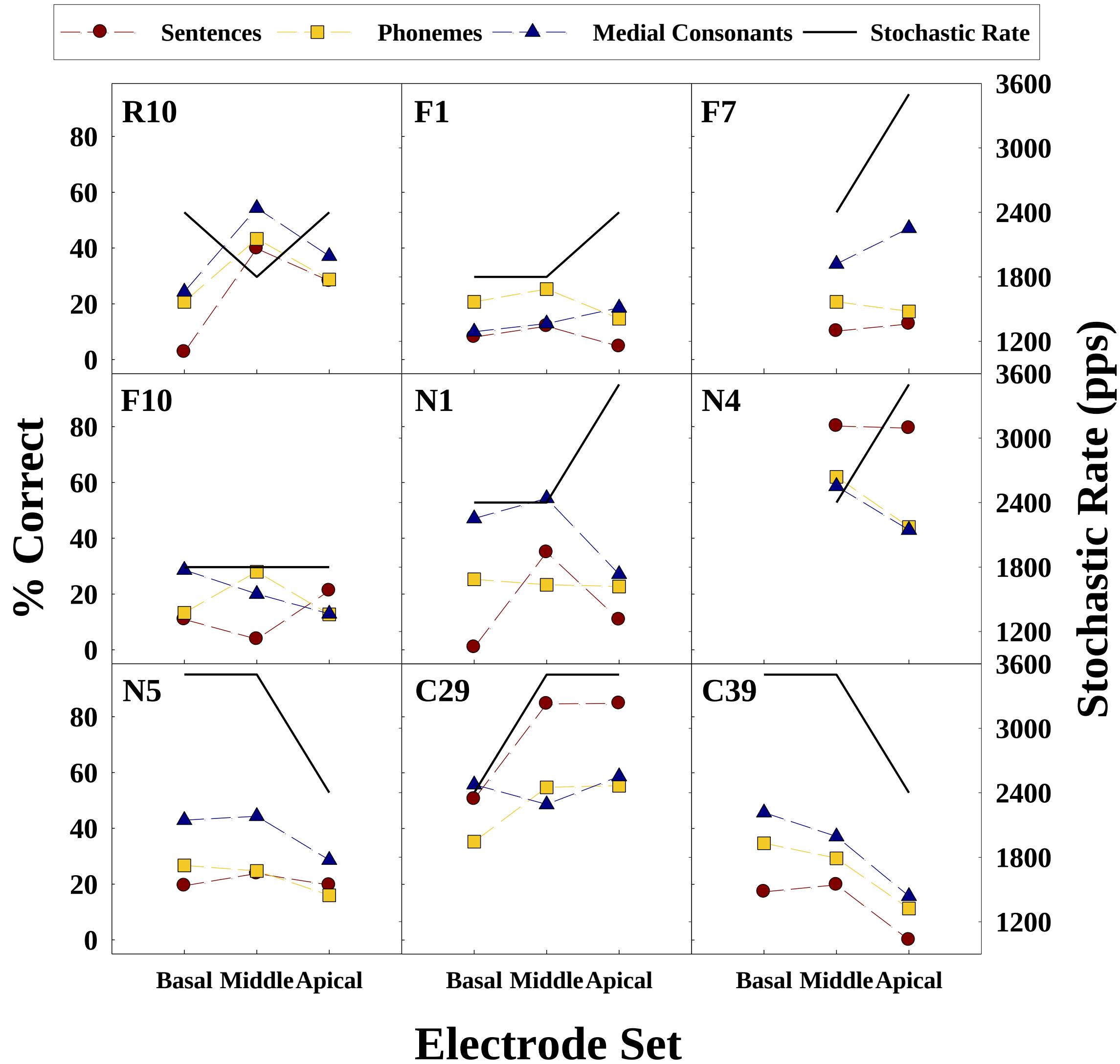

Figure 4. Individual patterns of performance (dashed lines and symbols, left axis) and stochastic rate (solid lines, right axis) across electrodes sets for the subset of nine subjects tested in both rate conditions. Data is given for HINT Sentences, CNC Phonemes, and Iowa Medial Consonants. Note that missing data points for subjects F7 and N4 are for basal maps that were not tested due to voltage compliance limits.

Chapter 4: Discussion and Conclusions

Cochlear Region

One purpose of this study was to determine which region of the cochlea contributed the most to speech perception among cochlear implant users. Cochlear region was estimated by stimulating electrodes in limited portions of the electrode array (basal, middle, apical). For sentences and phonemes, stimulating the middle electrodes resulted in better speech perception than the basal or apical electrodes. For these stimuli, group mean performance was significantly better for the middle electrodes and most subjects demonstrated their best performance when using the middle electrodes. For medial consonants, performance was similar for the basal and middle electrodes. There was no significant difference in mean score between these two electrode sets, although the mean was higher for the middle electrodes. Most subjects demonstrated their best performance using the basal electrodes, though there were also a large number of subjects who demonstrated their best performance using the middle electrodes. Because more subjects performed best using the basal electrodes, the mean of the basal electrodes would be expected to be higher than for the middle electrodes, which was not the case. This apparent discrepancy between group means and subject counts suggests that those subjects who performed best using the middle electrodes for medial consonants were higher overall performers than those who performed best using the basal electrodes.

Despite the significant findings for electrode set, variability in performance as a function of electrode set was noted across subjects for all stimulus measures. In Table 3, for example, there is at least one subject per stimulus who demonstrated their best performance at each of the electrode sets.

Differences in speech perception performance across the cochlea can be expected for several reasons. Neural survival can differ across the cochlea, particularly in individuals with hearing loss. The cause of a hearing loss may have resulted in auditory neural death that is extensive across the entire cochlea or limited to one region. This unpredictable pattern of neural death results in different amounts of auditory neuron activation in response to electrical stimulation across the cochlea (Shannon et al., 2001). More neurons respond in regions with better neural survival, which could be expected to lead to better speech perception. Those regions with very few surviving neurons would experience very little neural response to stimuli (Hall, 1990), potentially resulting in poorer speech perception (Firszt, Chambers, & Kraus, 2002). Another explanation for differences in performance across the cochlea may be related to the differences in the temporal response of the auditory nerve across the cochlea (Hughes et al., 2012; Wilson et al., 1997). One region may experience less synchronous firing than another region, or may be “more stochastic”. If desychronization of auditory neurons does in fact lead to better speech perception, then the cochlear region with less synchronous discharge patterns may allow for better speech perception. The results of the present study, however, do not suggest that this would be a cause for variation in performance across the cochlea.

The difference in optimal region across stimuli may be due to a number of differences between the sentences, phonemes in words, and medial consonants tasks. Sentences and words include vowels, which contain primarily low frequency information. Consonants, on the other hand, contain more high frequency information. It is likely that speech materials are more easily perceived in the cochlear region that corresponds to the frequencies with the most energy in the stimulus, as spectral mismatch has been shown to be detrimental to speech understanding (Rosen, Faulkner, & Wilkinson, 1999; Shannon, Zeng, & Wygonski, 1998). This may explain why more subjects demonstrated their best performance for medial consonants using basal electrodes, as high frequency information is coded in the basal region of the cochlea.

In addition, vowels and sentences require better spectral discrimination than consonants, which can be more easily distinguished on the basis of temporal information (Rosen, 1992; Rosen et al., 1999). As a result, vowels and sentences are more susceptible to the negative effects of spectral mismatch (Shannon et al., 1998). Adequate temporal information was presumably available to the subjects in this study, whereas frequency information was altered. This may help explain why, on average, performance was better for the medial consonants than for the other stimulus types. Subject counts for medial consonants were also less clear than the other stimuli in regards to an optimal region. Additionally, this was the only stimulus for which two subjects demonstrated equal and optimal performance with two electrode sets. These results may have occurred because consonants are less affected by modified spectral information and thus were less affected by stimulated cochlear region.

An additional consideration is context. Sentences contain contextual cues not found in phonemes within a word or medial consonants. Similarly, phonemes within a word contain contextual cues not found in medial consonants. Furthermore, the medial consonants were tested using a closed set recognition task whereas the sentence and word stimuli were open set tasks. These factors may have affected the level of difficulty in recognizing one type of stimulus compared to another.

The variation that was observed across subjects regarding which area of the cochlea allowed for the best speech perception scores may be due to the variability that exists between individuals with cochlear implants. Temporal responses of the auditory nerve vary among people as shown by differences in ECAP responses (Hay-McCutcheon, et al., 2005; Hughes et al., 2012; Wilson et al., 2007). These responses may be related to speech perception (Fu 2002; Rubinstein et al., 1999), which would account for some subject variability. In addition, just as auditory neural survival differs across regions of the cochlea, it also differs across subjects (Shannon et al., 2001). While neural survival may be predicted based on electrically evoked potentials (Hall, 1990), the extreme variation that could be expected among subjects would have been difficult to control for. There are also other variables that cannot easily be controlled for in cochlear implant research due to the limited number of subjects available and inherent variability involved in cochlear implantation. These variables, including duration and age of implantation, as well as speech perception performance when using a full electrode array, may have created differences in performance across subjects.

The results regarding cochlear region obtained by the present study are consistent with those found by Hochmair et al. (2003) and Pfingst et al. (2001), who also found the middle region to produce the best speech perception. However, the results of the present study are not in agreement with those found by Fu and Shannon (1999), Geier and Norton (1992), and Shannon et al. (2001). This discrepancy could be due to a number of factors. The present study's methodology was most similar to that of Hochmair et al. (2003) and Pfingst et al. (2001), where a subset of electrodes centered in either the basal, middle, or apical section of the array were stimulated. Fu and Shannon (1999) used a map with relatively widely spaced electrodes that was gradually shifted from the basal end to the apical end of the array. Geier and Norton (1992) and Shannon et al. (2001) removed sections of the electrode array to create holes in the map. These procedural differences may have contributed to differences in results across studies. Speech perception materials may also be responsible for variation in results across studies, as the present study found a different region of best performance for medial consonants than for sentences and phonemes. It is not likely that device or processing strategy played a role in variation across studies, as Hochmair et al. (2003) and Pfingst et al. (2001) obtained similar results to the present study using a Med-El COMBI 40+ with CIS and Nucleus 22 with SPEAK, respectively. The number of subjects included in each study may have been a factor, however. The present study included 22 ears, a greater number of subjects than any of the previously mentioned studies whose subject numbers ranged from three to 10 subjects with an average of seven subjects per study.

Stimulation Rate

No effect of stimulation rate was observed in this study. Differences in group mean performance using daily and stochastic rate were not significantly different for any stimulus task. In addition, daily rate scores were correlated with stochastic rate scores and the number of subjects demonstrating their best performance using daily rate was essentially equal to the number of subjects demonstrating their best performance using stochastic rate. One interaction between rate and region occurred for medial consonants where subjects performed better using stochastic rate than daily rate. This one instance may have occurred due to the small number of subjects included in the analysis. Overall, these findings do not support the hypothesis that a subject's stochastic rate will allow for better speech perception than their daily rate.

Speech perception varied by electrode set. However, as shown by Figure 4, this did not appear to be related to variations in stochastic rate by electrode set. Few subjects showed consistent patterns across stimuli that related either directly or inversely to the stochastic rate pattern across electrodes. These results suggest that variations in speech perception performance across different regions of the cochlea are not related to the stochastic rate variations across the cochlea.

The lack of significance in these results may have occurred for several reasons. Only a small number of subjects were able to participate using their stochastic rate due to device limitations or a lack of measurable ECAPs. It is also possible that the speech perception tasks in this study were too difficult for any effects of rate to become apparent. If subjects had been tested using a full electrode array, they potentially could have made better use of their stochastic rate. Using a full electrode array would not have been a suitable method for the present study, as a comparison with performance using a full electrode array with daily rate would have been inappropriate given the amount of experience with the regularly used map. It is also not clear at this time how the extended use of a subject's stochastic rate may affect speech perception results, as the present study did not allow for an acclimatization period. Future research will attempt to address these issues.

The results obtained by the present study are consistent with those found by previous studies including Verschuur (2005) and Weber et al. (2007) who found no effect of stimulation rate on speech perception. The results of the present study differ from those found by numerous other studies including Arora et al. (2009) Holden et al. (2002), Loizou et al. (2000), Nie et al. (2006), and Vandali et al. (2000). These studies suggest that as stimulation rate varies, so does speech perception. The difference in results across studies could be due to a number of factors. Again, it is not likely that the device or processing strategy had an effect on results. Verschuur (2005) used Ineraid and Med-El COMBI 40+ devices with CIS and obtained similar results to the present study, whereas Arora et al. (2009) used a Nucleus 24 device with ACE and obtained conflicting results. It is possible, though, that the variation in results across studies is due to the stimulation rates that were included in each study. Because it is not clear what effect stimulation rate has on speech perception, it is difficult to predict what variation may have occurred across studies as a result of using different stimulation rates. In addition, all of the previously mentioned studies (Arora et al., 2009; Holden et al., 2002; Loizou et al., 2000;

Nie et al., 2006; Vandali et al., 2000; Verschuur, 2005; Weber et al., 2007), including the present study, used a relatively small number of subjects. Subject numbers, including the present study, ranged from five to 13 with an average of eight subjects per study.

Study Limitations

One limitation of the present study is that when using a high stimulation rate there is a necessary reduction in pulse width. Smaller pulse widths are often perceived as being quieter to the cochlear implant user and thus an increase in amplitude is required. If amplitude is increased to a great enough extent, eventually it will cause an electrode to exceed its voltage compliance limit. For two subjects (N4 and F7) the basal map used with the stochastic rate, which was 3500 pps for both subjects, could not be tested. In one case, no perception of sound occurred before limits were reached and in the other, a comfortable loudness level could not be obtained. It is possible that pulse widths were too narrow for these subjects and amplitude could not be increased enough before compliance limits were met. Because of this voltage compliance issue, using a subject's stochastic rate as the stimulation rate may not be an option for some cochlear implant recipients or changes may need to occur in cochlear implant manufacturing before it is a possibility.

The restricted number of stimulation rates available in cochlear implant programming software is a second limitation of this study. Hughes et al. (2012) measured ECAPs at stimulation rates of 900, 1200, 1800, 2400, and 3500 pps. These stimulation rates were chosen because they are the rates available for the ACE processing strategy in Cochlear Corporation's Custom Sound 3.2 programming software (Cochlear Ltd., Lane

Cove, New South Wales, Australia). Stochastic rate was defined as the lowest of these stimulation rates at which there was no significant difference between odd and even numbered pulse amplitudes. It is a possibility, though, that a subject's stochastic rate could fall between two of these rates. In other words, it is possible that the alternation in amplitude could terminate at a rate that was not tested by Hughes et al. (2012) and therefore the subject's true "stochastic rate" was not actually determined. Similarly, for subjects with Advanced Bionics devices, the exact stochastic rate determined by Hughes et al. (2012) could not always be used in the present study due to limitations of the programming software. At this time, it is not known what effect small deviations from stochastic rate have on speech perception.

For the majority of the subjects who were tested using both their daily and stochastic rates, the stochastic rates were higher than the daily rate. However, in the two subjects in this subgroup who utilized an Advanced Bionics device (C29 and C39), their daily stimulation rates were higher than all of their stochastic rates. It is not clear what effect a further increase in stimulation rate beyond an individual's stochastic rate has on speech perception. In the present study, there was no consistent pattern for these two subjects in terms of optimal rate. Subject C29 performed better with stochastic rate in six of the nine region-stimulus combinations, whereas subject C39 performed better with stochastic rate in only four of the nine region-stimulus combinations. This topic requires further investigation before any conclusions can be drawn.

Effects of channel interaction also need to be taken in consideration. The stochastic rates used in the present study were based on per-channel rates. It is known, however, that significant overlap in neural excitation occurs between adjacent electrodes (Hughes & Abbas, 2006). Therefore, stimulation on adjacent electrodes, such as what occurred in the present study, could result in an overall faster stimulation rate for a given electrode's corresponding neural population than what was intended (Matsuoka, Rubinstein, Abbas, & Miller, 2001). Again, it is not clear what effect this would have on speech perception.

Another limitation of this study is that CT scans for subjects were not analyzed to verify a full insertion of the electrode array. This affords the possibility that a region of the cochlea was either partially or fully stimulated apart from the intended region. For example, if an electrode array is not fully inserted into the cochlea, delivering current via the apical electrodes may actually stimulate the middle section of the cochlea and delivering current via the basal electrodes may not stimulate any part of the cochlea. However, even with imaging available to confirm a full insertion, the actual region of the cochlea where the electrode array rests is not entirely predictable due to individual variations in cochlear length. Average cochlear length is 33-34 mm, but this can vary by up to 13.78 mm across individuals (Miller, 2007). As a result, even with a full insertion, it is difficult to judge exactly which region of the cochlea each part of the electrode array will stimulate. In the present study, some variation in actual stimulated cochlear region may have occurred across subjects due to electrode array insertion depth and/or variations in cochlear length. Consistency was maintained, however, across measures within subjects by keeping the basal, middle, and apical electrode sets constant. The purpose of this study was to find the relative region of the cochlea displaying the best speech perception scores for an individual, as differences across subjects were expected. Effects within subjects were the focus, making variations in electrode placement between subjects less of a concern.

Future Research and Conclusions

The present study determined the area of the cochlea that allows for the best speech perception score for an individual subject. The next step is to relate this to performance using a full electrode array. Future research will involve creating a map with the stochastic rate of the region producing the best speech perception. Subjects will then take that map home and become accustomed to using it in daily life. Performance can then be compared to performance using the full electrode array and daily stimulation rate.

The primary purpose of this study was to determine which region of the cochlea contributes the most to speech perception. The results of this study suggest that the middle electrodes of the array, and thus the middle region of the cochlea, may contribute the most to speech perception. The secondary purpose was to determine if differences in performance exist between the use of daily and stochastic stimulation rates. While ECAPs may be a potential indicator of optimal stimulation rate for a cochlear implant user, the results of the present study regarding use of the stochastic rate as optimal stimulation rate are unclear. Given the small number of subjects and difficulty of the speech perception tasks involved in this study, further research on the topic is warranted. Future research directed at using ECAPs to predict stimulation rate should take into consideration the auditory neural responses of the middle cochlear region.

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